Stepped-heterodyne optical complex spectrum analyzer

D. A. Reid,[1] S. G. Murdoch,[2,*] and L. P. Barry[1]

[1]*Research Institute for Networks and Communications Engineering, School of Electronic Engineering, Dublin City University, Dublin 9, Ireland*
[2]*Physics Department, University of Auckland, Private Bag 92019, Auckland, New Zealand*
**s.murdoch@auckland.ac.nz*

Abstract: We present a heterodyne measurement of the spectral amplitude and phase of periodic optical signals. In contrast to previous techniques this measurement requires no optical modulation of either the signal or the local oscillator, places much relaxed tunability requirements on the optical local oscillator, and requires no electronic clock to be passed to the receiver. We present measurements of the spectral amplitude and phase of 20 GHz 33% return-to-zero, and 66% carrier-suppressed return-to-zero optical signals, as well as a passively modelocked optical source with in excess of 100 modes.

OCIS codes: (120.5050) Phase measurement; (320.7100) Ultrafast measurements.

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1. Introduction

The measurement of the intensity and phase of optical waveforms has been a focus of extensive research, initially for the investigation of ultra-short laser pulses and more recently for optical arbitrary waveform generation and optical communication systems [1–13]. Advanced modulation formats, which were first developed in wireless communication systems, are now widely used in optical communications. These formats such as DPSK, DQPSK and QAM incorporate data on both the intensity and phase of the optical carrier. The development and optimization of these complex systems require improved phase sensitive measurement techniques.

In this paper we present a stepped-heterodyne measurement capable of recovering the spectral amplitude and phase of a periodic optical signal. The signal under test is mixed with an optical local oscillator positioned between two of the signal modes. The resultant beat signals, recorded on a real-time oscilloscope, allow the recovery of the amplitude of the two modes, as well as their phase difference. By stepping the local oscillator across all signal modes we obtain a complete measurement of the optical signal's amplitude and phase. The method has its origins in the linear techniques described in Refs [7–9]. where adjacent spectral modes are isolated using an optical monochromator and their phase difference determined using high-speed RF electronics. References [12,13] later showed how to adapt this technique to an optical heterodyne setup which allows significant improvement in the spectral resolution, sensitivity and dynamic range of the measurement. In the stepped-heterodyne technique we present here we show how the addition of a real-time oscilloscope to the RF detection system allows the spectral amplitude and phase of a periodic optical signal to be determined without the need for any optical modulation of either the local oscillator or the signal under test. The technique also permits a significant relaxation of the tunability requirements for the optical local oscillator, and requires no electronic clock (derived from the optical signal) to be passed to the receiver. This means that as well as the measurement of optical telecommunications sources, the technique is ideally suited to the measurement of passively modelocked devices and optical signals at wavelengths away from the primary telecommunications bands. To demonstrate the capabilities of this technique we present measurements of 20 GHz 33% return-to-zero (RZ), and 66% carrier-suppressed return-to-zero (CS-RZ), optical pulses generated from a Mach-Zehnder modulator (MZM). The phase and amplitude characteristics of these signals are well known [14], and we find good agreement between our results and independent measurements of the signals' optical spectrum and temporal intensity. We are also able to demonstrate the measurement of a passively modelocked source with a repetition rate of 10 GHz and a spectrum consisting of in excess of 100 modes.

2. Theory

The complex optical spectrum analyzer we present is designed to measure the complex electric field of periodic optical signals. The periodic nature of the signal reduces its spectrum to a series of discrete spectral modes spaced at multiples of the repetition rate. Our measurement, in common with the two heterodyne complex optical spectrum measurements described in references [12,13], works by measuring the amplitude of each mode, as well as the phase difference between adjacent modes. From here it is simple to reconstruct the full electric field of the input signal in either the time or the frequency domain. The key difference between this work and that reported in [12,13] is the use of a digital real-time acquisition of the RF beat spectrum between the signal and the local oscillator. This allows the measurement to proceed without the need for either an external electronic clock, or optical modulation of the signal or local oscillator.

The electric field of the periodic signal we wish to measure can be written as,

$$E_{sig}(t) = \sum_{m=-N}^{N} \left(\sqrt{P_m}\exp(jm\Omega t + j\phi_m)\right)\exp(j\omega_s t + j\phi_s(t)) \tag{1}$$

where $2\pi/\Omega$ is the period of the signal, P_m is the power of the m$^{\text{th}}$ mode, ϕ_m is the spectral phase of the m$^{\text{th}}$ mode, ω_s is the signal's optical frequency, and $\phi_s(t)$ is the phase noise of the optical carrier. This signal is then mixed with an optical local oscillator, $E_{LO}(t) = \sqrt{P_{LO}}\exp\left(j\omega_{LO}t + j\phi_{LO}(t)\right)$, where P_{LO}, ω_{LO} and $\phi_{LO}(t)$ represent the power,

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optical frequency and phase noise of the local oscillator. The local oscillator is detuned by a frequency δ from the k[th] mode of the signal. The measurement requires that the detuning δ is less than $\Omega/2$ as illustrated in Fig. 1.

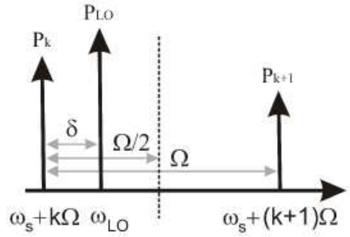

Fig. 1. Spectral offset between k[th] and (k + 1)[th] signal modes, and the local oscillator.

The mixed signal is then detected on a high-speed photodiode, and the detected photocurrent amplified and then recorded by a real-time oscilloscope. Provided the bandwidth of the detection system is larger than Ω the detected signal can be written as:

$$\begin{aligned} V_{sig}(t) \propto & \sqrt{P_{LO}P_k}\cos\left(\delta t + \phi_{LO}(t) - \phi_s(t) - \phi_k\right) \\ & + \sqrt{P_{LO}P_{k+1}}\cos\left(\left(\Omega - \delta\right)t - \phi_{LO}(t) + \phi_s(t) + \phi_{k+1}\right) \\ & + \sum_{m=-N}^{N-1}\sqrt{P_m P_{m+1}}\cos\left(\Omega t + \phi_{m+1} - \phi_m\right) + \text{ DC terms} + \text{frequencies higher than } \Omega \end{aligned} \quad (2)$$

The first and second terms of Eq. (2) represent the beat signal between the local oscillator and the k[th] and (k+1)[th] modes respectively. The third term is the sum of the beat signals between adjacent modes of the periodic signal and can be written as a single cosine wave at frequency Ω: $A_{TOT}\cos(\Omega t + \phi_{TOT})$. From here the procedure is to digitally filter the signals at δ, $\Omega - \delta$, and Ω, then multiply together the filtered signals at δ and $\Omega - \delta$. Calculating the phase difference between the component of this multiplied signal at Ω and the original filtered signal at Ω allows the extraction of the phase difference $d\phi = \phi_{k+1} - \phi_k - \phi_{TOT}$, with complete cancellation of the phase noise of both the signal and the local oscillator. The relative power in the k[th] mode can likewise be determined by calculating the power in the filtered signal at δ. This procedure is illustrated schematically in Fig. 2. We note that whilst the scheme presented here is purely digital, it could also easily be implemented in analog electronics if required. This would result in a considerably lower cost receiver, although without some of the flexibility of an all-digital receiver.

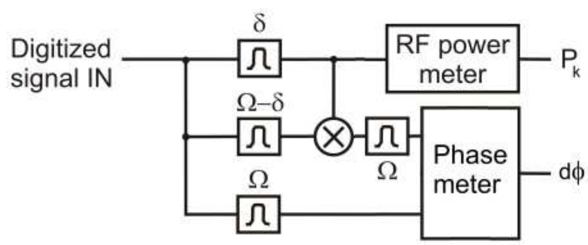

Fig. 2. Numerical algorithm used to extract the relative power of the k[th] mode and the phase difference between the k[th] and the (k+1)[th] mode of the optical signal under test.

In practice some care must be taken in setting the bandwidths of the three digital band-pass filters at δ, $\Omega - \delta$, and Ω in order to obtain an optimum reconstruction of the signal's complex electric field. The spectral width of the signals at δ and $\Omega - \delta$ are set by the phase noise of both the signal under test and the local oscillator. This requires the bandwidth of the filters be set wide enough so as not to significantly clip any of this spectral information. The

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signal at Ω arises from the beating between adjacent modes of the periodic signal and as such is typically much narrower than the other two filtered signals and can be filtered more tightly. The exact filter bandwidth required for each signal can be simply determined by examining the RF spectrum of the acquired signal. A sample RF spectrum (2^{16} points, acquired at 40 GS/s) showing the beating between the local oscillator (an external cavity laser (ECL) with a linewidth ~100 kHz) and two adjacent modes of a 10 GHz externally modulated DFB source (linewidth ~10 MHz) is shown in Fig. 3. The three signals of interest are clearly visible. Using raised-cosine ($\beta = 0.5$) band-pass filters with a 3 dB pass-band of 100 MHz for the two beat signals at δ and $\Omega - \delta$, and 10 MHz for the signal at Ω ensures no spectral information is lost, allowing for accurate cancellation of the phase noise of the signal and the local oscillator. Inset in Fig. 3. is the recovered phase difference between the two modes as a function of time. The phase difference $d\phi = \phi_{k+1} - \phi_k - \phi_{TOT}$ is calculated from the mean of this signal, and its standard error can be used to assess the statistical error in the phase measurement. However in general it is not possible to use the statistical error of the phase measurement to assess the accuracy of the reconstructed signal as this requires additional information about the phase noise properties of the source not available from this simple mixing arrangement.

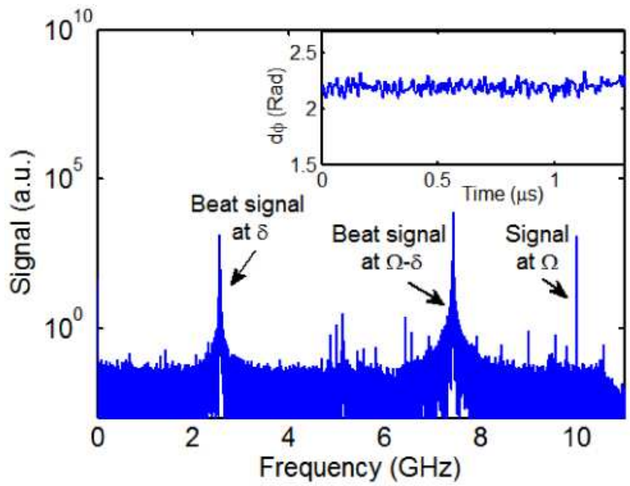

Fig. 3. Sample RF beat spectrum calculated from a real-time acquisition of the beating between a local oscillator and two adjacent signal modes of a 10 GHz source. Inset: the recovered phase difference.

The full measurement then consists of simply stepping the local oscillator across all modes of the signal under test, repeating the above procedure at each point. The phase of each mode can then be calculated by integrating the measured phase differences. The fact that we are only able to determine the phase difference between adjacent modes up to a constant offset (set by ϕ_{TOT}) does not significantly effect the reconstruction of the signal. In the time domain this offset simply results in an overall temporal shift in the reconstructed signal and in the frequency domain it appears as a constant offset to the measured spectral group delay which can be easily removed if desired [7].

The measurement described here requires neither any optical modulation of the signal or the local oscillator, nor an electronic clock to be passed to the receiver. In addition it only requires the local oscillator to be positioned to within an accuracy of $\Omega / 2$ of each mode. This considerably reduces the requirements for the tunablity of the local oscillator. For example, a 10 GHz signal under test only requires the local oscillator to be positioned to within 5 GHz of each mode, opening up the possibility for the use of discretely-tunable low-cost local oscillators such as sampled-grating DBR (SG-DBR) lasers. The measurement does however come with one caveat: it requires the signal under test to possess an intensity modulated component at Ω (the repetition rate of the signal). Without this, the calculation of the phase difference between adjacent modes is not possible. Some signals, for example a purely phase modulated signal, will not satisfy this condition (ie A_{TOT} is strictly zero). In these cases an electronic clock (at Ω) will need to be passed to the receiver in order for the measurement to work. In practice however, this limitation is not as severe as it may first appear as most signals, even those that theoretically do not possess any intensity modulation at Ω, do usually contain a small residual intensity modulation at Ω that allows the recovery to proceed. We demonstrate this in the results section that follows where we consider a 66% CS-RZ signal. In principle this signal should not contain any intensity modulation at the fundamental repetition rate, however we are able to show that the small residual intensity modulation that remains at Ω is indeed sufficient to make a successful measurement. Also we note that in addition to the above requirement the measurement requires a non-zero power to be present in each spectral mode of the signal under test. Any missing modes (e.g. as might be found in a strongly carrier suppressed signal) will prevent the measurement from working correctly. This is because it is not possible to integrate the measured phase difference between adjacent modes across gaps in the spectrum. Finally we note that the measurement, as presented, is polarization sensitive, with only the component of the signal polarized parallel to the local oscillator measured. If required, polarization resolved measurements of the signal under test using this technique can be simply implemented by direct application of the polarization diverse schemes developed for optical coherent receivers.

3. Experiment

The experimental setup for this technique is shown in Fig. 4. The signal under test is mixed with an optical local oscillator (a continuously tunable, 100 kHz linewidth ECL), before detection by an amplified photodiode (11 GHz bandwidth). The mixing is performed using a simple 50/50 coupler rather than an optical hybrid as the asymmetric placement of the local oscillator between the two modes under test allows us to unambiguously identify the beat signal associated with each mode. The resultant signal is captured on a 40 GS/s real-time oscilloscope (10 GHz bandwidth). The total bandwidth of the detection system sets the maximum repetition rate of the optical signal under test that can be measured by the system. A polarization controller in the local oscillator arm is used to ensure the two waves are collinearly polarized. Measurements are taken by discretely tuning the local oscillator so that it lies between successive adjacent modes as described in the previous section, and at each point acquiring a 1.64 µs signal trace (40 GS/s, 2^{16} samples).

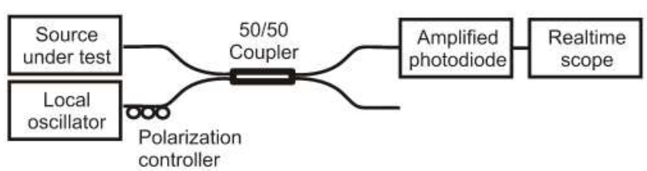

Fig. 4. Schematic diagram of the complex optical spectrum analyzer.

The first source we wish to measure is a continuous-wave DFB laser externally modulated by an $LiNbO_3$ Mach-Zehnder modulator. The modulator drive signal at 10 GHz is set just below $2V_\pi$ (peak-to-peak), and the bias is set to the null to generate 20 GHz 66% CS-RZ pulses, and to the peak to generate 20 GHz 33% RZ pulses [14]. For this measurement the average power in both the signal and the local oscillator was 1 mW. The reconstructed temporal and spectral complex electric fields for the 66% CS-RZ and 33% RZ signals are plotted in Fig. 5 as blue circles in the spectral domain, and blue curves in the time domain. The measured temporal phase response of these signals shows the expected behaviour with π phase jumps between adjacent pulses of the 66% CS-RZ signal, and alternating chirp between adjacent pulses of the 33% RZ signal [14]. To further validate these results the two signals were also measured using a high-resolution optical spectrum analyzer (resolution 1 pm) and a

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50 GHz photodiode and a sampling oscilloscope. These independent measurements of the optical spectrum and temporal intensity are plotted in Fig. 5 as red curves and show excellent agreement with the stepped-heterodyne measurements. From these results we are able to infer a dynamic range for the instrument of in excess of 45 dB, and a sensitivity of better than 10 nW/mode (for an SNR = 1).

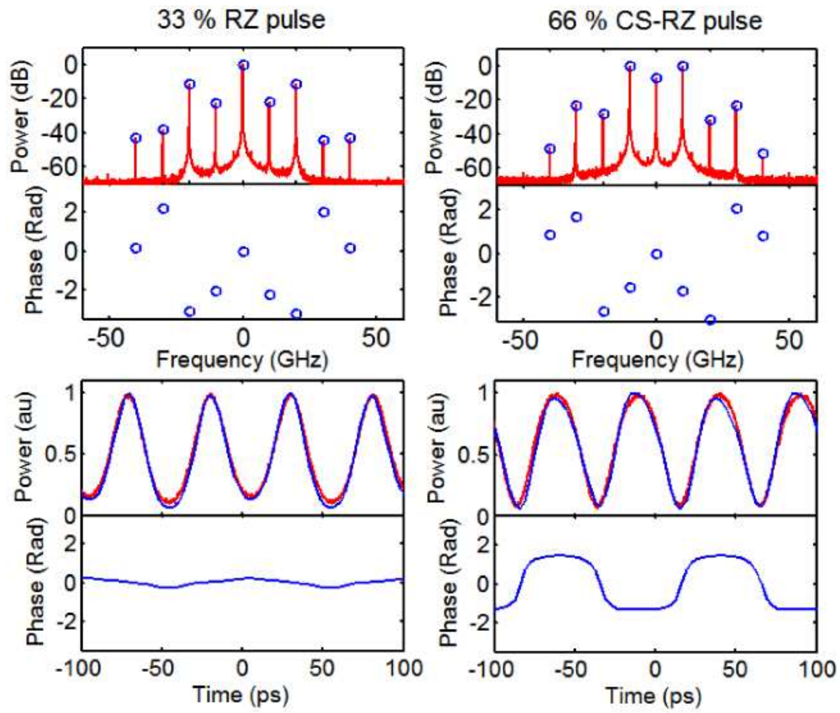

Fig. 5. Temporal and spectral reconstruction of the complex electric field for 20 GHz 33% RZ pulses, and 20 GHz 66% CS-RZ pulses. The blue circles show the reconstructed spectral intensity and phase, the blue lines reconstructed temporal intensity and phase. The red curves show independent measurements of the pulse's spectral and temporal intensity profiles.

Finally we wish to demonstrate the capability of the instrument to measure a passively modelocked source for which no external clock is available. The source we choose to measure is a passively modelocked laser centered around 1555 nm with a repetition rate of 10 GHz and a pulse width of 2 ps. This is a challenging measurement as the average power of the source is only 100 μW spread over more than 100 modes. This means the average power in the outlying low power modes approaches the sensitivity limit of the instrument. In Fig. 6 we plot the spectral intensity and phase of the source measured directly after the source (green circles), and after propagation through 220 m of dispersion compensating fiber (DCF) (blue circles). The spectrum of the laser is also measured with an independent high resolution optical spectrum analyzer (plotted in red). The inset to Fig. 6 shows the reconstruction of the temporal amplitude and phase of the pulse before propagation through the DCF.

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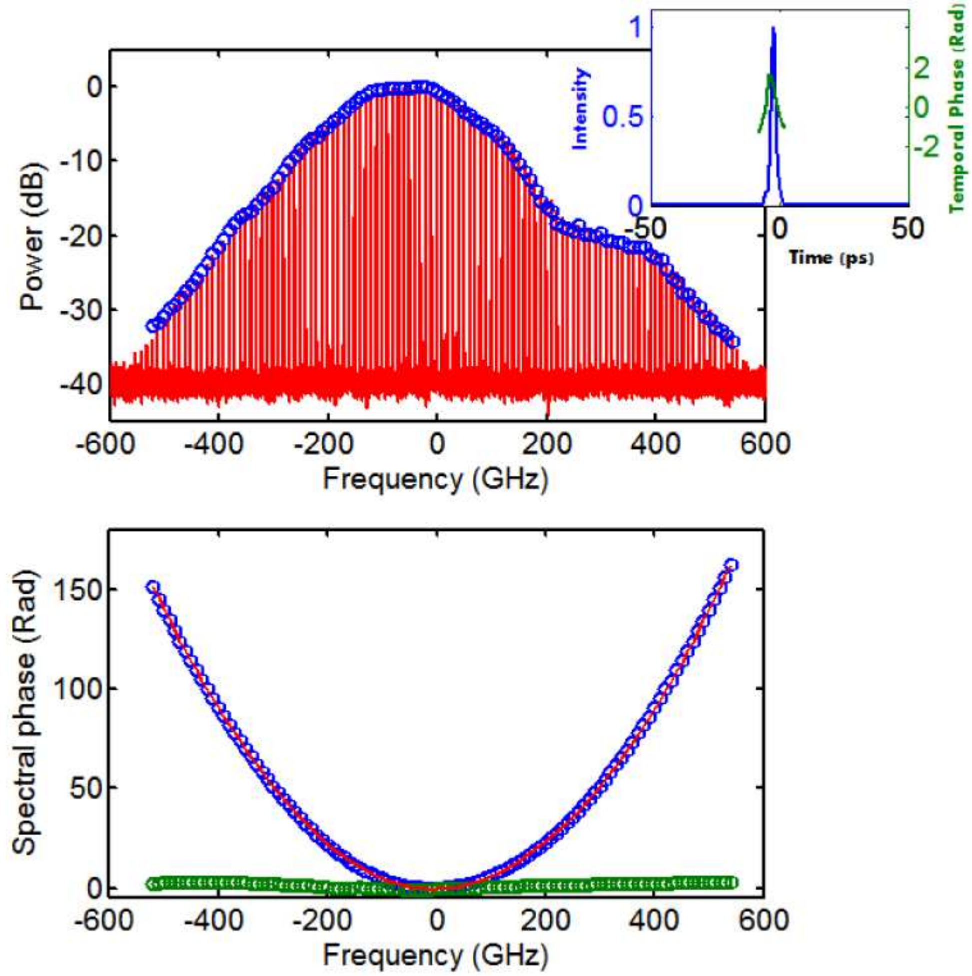

Fig. 6. Spectral reconstruction of a passively modelocked source: measured directly after source (green circles), and after 220 m of DCF (blue circles). The red traces show the independently measured power spectrum of the source, and a fit to spectral phase using a quadratic dispersion of 30.9 ps^2 and a cubic dispersion of 0.24 ps^3. Inset is the reconstruction of the temporal amplitude and phase of the pulse before propagation through the DCF.

The distinctive quadratic phase profile resulting from propagation through a dispersive fiber is clearly visible on the recovered spectral phase measured after 220 m of DCF. The red curve plotted on top of the spectral phase measurements is the sum of the spectral phase of the source measured before the DCF and a quadratic dispersion of 30.9 ps^2 (140.6 ps^2/km) and a cubic dispersion of 0.24 ps^3 (1.09 ps^3/km). This curve shows an excellent agreement with the measured spectral phase after 220 m of DCF and provides us with a simple check of the accuracy of our spectral phase measurement. The group delay of the signal can be calculated directly as the differential of the spectral phase with respect to the angular frequency. In Fig. 7 we plot the measured group delay accumulated in the 220 m of DCF (blue circles) and the predicted group delay using the 2nd and 3rd order dispersion coefficients quoted above (red line). We also plot the difference between these two curves (green circles) which represents the error in our measurement. Figure 7 shows an excellent agreement between the two curves with a standard error in measured group delay of 1.5 ps. Figure 7 also shows that the standard error in the measurement is considerably better than this for the higher power modes (those between −400 and + 200 GHz where the power of the

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modes is within 20 dB of the central mode). Here the standard error in the group delay is less than 1 ps.

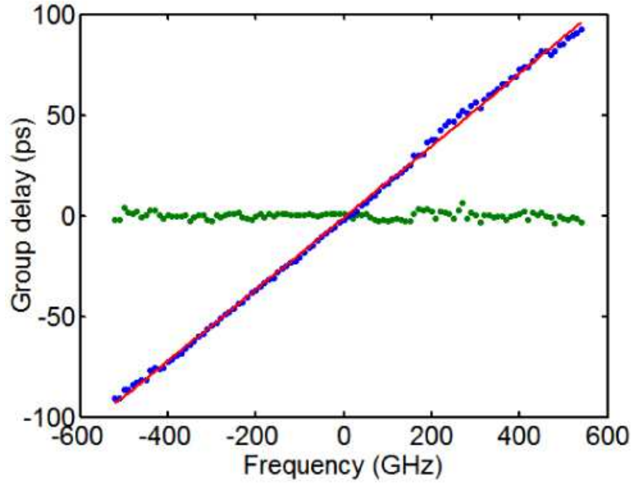

Fig. 7. Measured group delay of the 220 m of DCF (blue circles), and the best fit group delay using a quadratic dispersion of 30.9 ps^2 and a cubic dispersion of 0.24 ps^3 (red line). The difference between these two curves is plotted (green circles) and shows a measured standard error in the group delay of 1.5 ps.

4. Conclusion

We have presented a novel technique for the measurement of the intensity and phase of periodic optical signals via stepped-heterodyne analysis. The heterodyne nature of the measurement ensures excellent sensitivity and dynamic range. The technique has the advantage of requiring no optical modulators or filters, and no electronic clock or external optical phase reference. The technique only requires that the local oscillator is correctly positioned to within $\Omega/2$ of each mode, allowing for the possible use of a low-cost discretely tunable laser as the optical local oscillator. In addition, we have shown how the digital receiver could be replaced by an all-analog version resulting in a considerably lower cost system, albeit one with less flexibility. The system as presented should be capable of measuring short (less than 100 bit) pseudo-random bit-sequences (PRBS) encoded using coherent modulation formats. As such it could prove a useful tool for setup and analysis of coherent optical communication systems.

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